Hydraulic Conductivity of Ohio's Glaciated Soil, Its Implications, and Suggestions for Future Studies[1]

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ABSTRACT: Since 1999, hydraulic conductivity values in till have been measured by the laboratory standard test method ASTM D 5084 on undisturbed soil samples taken at depths between 3.0 m to 6.0 m (10 to 20 ft) in glacial till soils in western Ohio. Their rates on uncracked soil vary from 10^{-6} cm/sec to 10^{-9} cm/sec. Measurements made on till with cracks vary from 10^{-5}cm/sec to 10^{-8} cm/sec. Suggestions are made for future studies.

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INTRODUCTION

In recent years the existence of cracks in glacial till and their affect on soil hydraulic conductivity has aroused interest. A meeting was held in the field at a large test pit dug into cracked till at the Ohio State University's Molly Caren Agricultural Center near London in Madison County. A one-day conference was held over a year later. Nine articles on this subject were subsequently published in *The Ohio Journal of Science* June/September 2000 special issue, titled "Fractures in Ohio's Glacial Tills." The purpose of this article is to comment on observations made on till during explorations for manure holding ponds, and the importance of cracks in affecting the overall hydraulic conductivity of the soil.

In their article, Brockman and Szabo (2000) describe fracture patterns and depths at which cracks disappear. They also mention reports in which G. E. Grisak and others suggest that fractures in till may be due to "desiccation, freeze-thaw cycles, shearing from overriding ice, stress relief from removal of glacial ice, crustal rebound, regional tectonic stresses, and volume change from geochemical processes."

Storage of animal manure is of prime concern to livestock farming operations. The manure-water mixture is placed in large holding ponds. The size of these ponds can be greater than 60 × 60 m (200 × 200 ft) in area and 4.5 m (15 ft) deep. The ponds are filled with manure for several months; they are then emptied and the manure is used as crop fertilizer. Manure is also permanently stored in lagoons that are much larger. Livestock farms that have over 1000 animal-units presently require a permit from Ohio EPA to operate. The permit is based on the subsurface foundation, design of the facility, and its proposed operation.

As part of his work, the author has made over 200 subsurface explorations in Ohio in the past 10 years at sites where manure holding ponds will be excavated. The explorations consisted of test pits dug by backhoe and trackhoe at 0.9 m to 1.5 m (3.0 to 5.0 ft) depths below the proposed bottoms of the facilities. Soils were visually classified and logged using the ASTM Unified Soil Classification System, ASTM D 2488 (2001), which is an engineering classification. Soil types, their descriptions, and water movement into the pits were noted, as well as estimations of soil mechanics properties.

The greatest number of livestock-farming operations occurs within the glaciated part of the State. Cracks in till are evident at many sites. They are easiest to see in the gray unoxidized portion of the till, generally below 3.0 m (10 ft), where the cracks show up as brown iron-stained seams. The cracks extend to approximately 4.5 m (15 ft) of depth and frequently disappear between that depth and 6.0 m (20 ft). In 2000, Brockman and Szabo described observations by people who found fractures that disappeared at 4.5 m (15 ft), although some extended as deep as 33 m (108 ft). The latter are probably quite unusual. It is probable that most cracks disappear with depth as the pressure of the overlying soil causes them to close.

Shallow cracks in till near the surface of the ground may permit the possibility of horizontal leakage of manure-contaminated water into tile lines and ultimately into streams, but the frequency of this happening is not known. This potential problem is not addressed in this paper.

MATERIALS AND METHODS

Beginning in 1999 as part of the subsurface explorations, undisturbed (core) soil samples were taken from depths below the bottom of the lagoons. The purpose was to determine the hydraulic conductivity of the soil, and estimate how quickly water could move through soil below the bottom of a pond to contaminate an aquifer. Samples were obtained by driving a 10.2 mm (4.0 in) O.D. thin-wall steel cylinder that fits into a hand-operated density drive sampler (ASTM D 2937 2001). Where cracks were evident, the cylinder was placed to include a crack within it. The cylinders were dug up, capped, and tested. Four independent laboratories performed tests to provide the data. An advantage of this type of sampler is that a sample may be taken horizontally or vertically at any location in a test pit; the major disadvantage is that the size of the sample is small compared to *in situ* hydraulic conductivity tests made in the field using a drill rig.

Permeability tests to determine the hydraulic conductivity were performed on the samples in accordance with ASTM D 5084 (2001), using the falling head method and calculations. Density and Atterberg Limits tests were also performed. Table 1 lists the tabulation of the results.

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Table 1

Laboratory hydraulic conductivity of Ohio soil.

County	Township	Section	Soil Type	Soil Origin	Depth Ft	Dry Density PCF	Cracks in Soil	Atterberg Limits Liquid Limit	Atterberg Limits Plastic Index	% Natural Moisture	Permeability cm/sec
Clark	Madison	5	CL	Till	8.5 - 9.0	121.7	No			13.2	3.0 x 10E-8
Clark	Madison	5	CL	Till	9.0 - 9.5	124.5	No			13.4	3.9 x 10E-8
Darke	Greenville	24	CL	Till	14 .0 - 14.5	119.5	YES				2.6 x 10E-6
Darke	Jackson	17	CL	Till	15 .0 - 15.5	114.0	No	35	17	17.0	4.7 x 10E-6
Darke	Jackson	17	CL	Lacustrine	18.0?	109.5	YES	35	16	20.2	5.2 x 10E-6
Darke	Mississinawa	14	CL	Till	16 .0 - 16.5	122.8	No	25	10	12.6	2.2 x 10E-8
Darke	Mississinawa	14	CL-ML	Till	16.5 - 17.0	122.7	No	24	9	13.1	3.4 x 10E-8
Darke	Patterson	12	CL	Till	16.0 - 16.5	118.6	No	27	10	14.7	1.7 X 10E-6
Darke	Patterson	12	CL	Till	15.0 - 15.5	119.6	YES - HOR	29	12	14.1	1.4 x 10E-8
Darke	Patterson	12	CL	Till	8.5 - 9.0	116.8	No - w/Sand	31	13	15.2	5.0 x 10E-7
Darke	Wabash	7	CL	Till	11.0 - 11.5	116.9	No			16.5	6.9 x 10E-8
Darke	Wabash	7	CL	Till	11.5 - 12.0	126.0	No			5.0	1.1 x 10E-8
Darke	Wabash	4	CL	Lacustrine	8.0 - 8.5	107.0	No	39	21	21.2	2.0 x 10E-8
Defiance	Mark	4	CL	Lacustrine	9.0 - 9.5	99.9	No	45	24	24.6	4.7 x 10E-8
Hardin	Blanchard	33	CL	Till	13.5 - 14.0	122.5	No	28	10	13.3	2.0 x 10E-8
Hardin	Blanchard	33	CL	Till	13.5 - 14.0	116.3	No	29	13	14.2	2.4 x 10E-8
Hardin	Blanchard	33	CL	Till	15.0 - 15.5	120.5	No	25	9	14.6	6.6 x 10E-8
Knox	Union	24	CL	Till	15.0 - 15.5	109.8	No	31	13	13.9	1.4 x 10E-7
Loraine	Pittsfield	Rt 55 & Hughes	CL	Till	14.0 - 14.5	126.2	No			12.0	1.5 x 10E-8
Loraine	Pittsfield	Rt 55 & Hughes	CL	Till	14.0 - 14.5	121.0	No			12.8	2.4 x 10E-8
Mercer	Butler	4	CL	Till	12.0 - 12.5	112.1	YES	35	14	17.6	2.7 x 10E-7
Mercer	Butler	32	CL	Till	10.5 - 11.0	120.5	YES	28	12	13.6	7.2 x 10E-7
Mercer	Butler	32	CL	Till	10.5 - 11.0	116.8	YES	39	23	13.2	7.7 x 10E-6
Mercer	Butler	32	CL	Till	17.0 - 17.5	122.5	YES	25	10	14.4	1.0 x 10E-7
Mercer	Franklin	31	CL	Till	6.0 - 6.5	118.3	Few	29	11	14.2	1.1 x 10E-7
Mercer	Granville	30	CL	Lacustrine	12.3 - 12.7	92.8	YES - HOR	34	14	28.6	4.6 x 10E-6
Mercer	Granville	30	CL	Lacustrine	9.5 - 10.0	98.6	YES - VERT	38	16	25.0	2.1 x 10E-5
Mercer	Marion	2	CL	Till	13.5 - 14.0	121.5	No	24	8	28.6	3.1 x 10E-7
Mercer	Marion	12	CL	Till	18.0 - 18.5	125.3	No			11.2	1.5 x 10E-8
Mercer	Marion	12	CL	Till	15.5 - 16.0	120.7	No			13.4	1.3 x 10E-8
Mercer	Marion	12	CL	Till	15.0 - 15.5	108.0	No			20.4	1.5 x 10E-8
Mercer	Marion	12	CL	Till	15.5 - 16.0	120.9	YES			13.5	4.1 x 10E-8
Mercer	Marion	21	CL	Till	16.5 - 17.0	123.4	No	24	9	13.0	3.4 x 10E-7
Mercer	Marion	23	CL	Till	16.0 - 16.5	121.7	YES	25	10	13.7	3.3 x 10E-5
Mercer	Recovery	2	CL	Till	12.0 - 12.5	112.1	YES - VERT	34	18	13.6	5.8 x 10E-8
Mercer	Recovery	2	CL	Till	12.0 - 12.5	113.2	YES - HOR	32	13	13.6	1.7 x 10E-7
Mercer	Recovery	17	CL	Till	15.0 - 15.5	124.3	No	23	8	12.2	1.8 x 10E-8
Mercer	Recovery	17	CL	Till	16.5 - 17.0	124.7	No	23	9	12.2	1.8 x 10E-8
Paulding	Latty	11	CL	Till	17.5	114.1	No			17.9	1.6 x 10E-8

TABLE 1 (*Cont.*)

Laboratory hydraulic conductivity of Ohio soil.

County	Township	Section	Soil Type	Soil Origin	Depth Ft	Dry Density PCF	Cracks in Soil	Atterberg Limits Liquid Limit	Plastic Index	% Natural Moisture	Permeability cm/sec
Paulding	Latty	11	CL	Till	16.0	116.0	No			16.1	6.7 x 10E-9
Paulding	Paulding	6	CL	Till	12.0 - 12.5	104.6	No				3.0 x 10E-8
Paulding	Paulding	6	CL	Till	12.0 - 12.5	114.3	YES	32	17	14.6	3.9 x 10E-8
Paulding	Paulding	6	CL	Till	12.0 - 12.5	118.0	YES	30	14	13.3	1.3 x 10E-8
Paulding	Washington	17	CL	Till	17.0 - 17.5	126.8	No			12.2	6.4 x 10E-9
Paulding	Washington	17	CL	Till	13.0 - 13.5	114.3	No			18.3	1.4 x 10E-8
Putnam	Palmer	15	CL	Till	24.0 - 26.0	100.4	No			20.5	2.7 x 10E-8
Putnam	Palmer	15	CL	Till	11.0 - 13.0						5.7 x 10E-8
Shelby	Franklin	32	CL	Till	10.5 - 11.0	112.7	YES - HOR	32	12	14.9	1.1 x 10E-5
Shelby	Jackson	36	CL	Till	8.0 - 8.5	121.2	YES				1.5 x 10E-7
Shelby	Jackson	36	CL	Till	8.0 - 8.5	116.5	YES				2.5 x 10E-7
Union	York		CL	Till	14.5 - 15.0	123.3	No	26	10	11.2	2.6 x 10E-7
Union	York		CL	Till	17.0 - 17.5	111.2	YES	34	18	15.3	1.2 x 10E-6
Union	York		CL	Till	17.0 - 17.5	116.0	No	27	16	15.3	1.8 x 10E-8
Union	York		CL	Till	12.0 - 12.5	124.1	No	24	9	13.7	1.4 x 10E-7
Williams	Bridgewater	4	CL	Till	17.5 - 18.0	113.1	No			15.7	9.4 x 10E-9
Williams	Bridgewater	4	CL	Till	17.5 - 18.0	109.9	YES			16.3	2.5 x 10E-8
Williams	Jefferson	3	CL	Till	12.0 - 12.5	111.9	No			18.6	1.1 x 10E-8
Williams	Jefferson	3	CL	Till	11.0 - 11.5	120.7	No			13.8	1.5 x 10E-7
Williams	Jefferson	3	CL	Till	11.0 - 11.5	115.4	No			16.0	2.3 x 10E-8
Wood	Grand Rapids	21	CL	Till	14.0 - 14.5	118.1	No			14.3	1.7 x 10E-7
Wood	Grand Rapids	21	CL	Till	14.0 - 14.5	121.1	No			14.0	4.6 x 10E-9

Note: HOR = Horizontal, VERT = Vertical
All hydraulic conductivity tests were vertical measurements except for a horizontal measurement made in the Mercer County lacustrine sample.
Depth measurements were made in customary antiquated English units by placing a survey rod at the bottom of the test pit.

RESULTS

Test results indicate that water moves very slowly through glacial till, which coincides with results reported by others. Most glacial till in Ohio would be classified in the Unified Soil Classification System as lean clay (CL), and similar low hydraulic conductivity rates should be expected in areas that were not tested. Higher rates should be expected in areas where the till is sandy or if small lenses of sand or gravel are present within the overall matrix of till. Tests made on soil with horizontal and vertical cracks yielded slow to moderate hydraulic conductivity rates, varying from 10^{-5} cm/sec to 10^{-8} cm/sec. These rates are comparable to those reported by Fausey and others (2000) in their *Ohio Journal of Science* article. Their finding concluded the average hydraulic conductivity in till fractures at the Molly Caren site was 1.25×10^{-5} cm/sec while the unfractured till had a conductivity of 1.11×10^{-6} cm/sec, 10 times slower.

Another way to look at the hydraulic conductivity data in the table would be to consider the natural moisture versus the dry density. Soil mechanics tests show that hydraulic conductivity decreases when soil is compacted at a higher density and high moisture content, compared to compaction at a high density but lower moisture content. Additional testing on these (or similar soils) would show that a high number of soils listed in the table are preconsolidated (soil that is well compacted by the weight of glacial ice). Soil mechanics tests show that the moisture in soil decreases as the density of soil increases. Therefore these preconsolidated soils should have a low moisture content and low hydraulic conductivity.

DISCUSSION

Seepage velocity of water through till is determined by the hydraulic conductivity of the soil and is driven by the hydraulic gradient. The thickness of till below the bottom of a manure holding pond and an aquifer also affects the length of time for an effluent to move from a pond into an aquifer. Water wells logs indicate that aquifers can lie 15 m to over 45 m (50 to 150 ft) below the surface of the ground. The measured hydraulic conductivity rates when used alone suggest that it would take tens to hundreds of years for manure-contaminated water to reach an aquifer. During this time bacteria and natural processes could dilute and hopefully clean up any contamination before it reaches the aquifer. Aquifers in Ohio are ultimately fed by rainwater percolating downward through the soil, but the length of time for this to happen is unknown. The time for surface water to enter an aquifer should be faster in areas where till is thin, or bedrock is exposed in rock quarries and stream channels, than in areas where thick till covers bedrock.

The movement of water through a soil blanket below a pond is a soil mechanics seepage problem. Specific discharge calculations made according to Geotechnical, Design, and Construction Guidelines (USDA 1997), take into consideration the hydraulic head. The loss of water through a unit area is governed by:

$$v = k\left(\frac{H+d}{d}\right)$$

v = Specific discharge of water (v = Greek letter mu)
k = Hydraulic conductivity rate of soil
H = Hydraulic head of water
d = Thickness of a soil blanket below a pond

The seepage velocity of water leaking out of a pond is equal to:

$$\text{Seepage Velocity} = v \div n$$

n = porosity

The porosity of soil is the ratio, expressed as a percentage of the volume of the voids divided by the total volume of a soil mass. It is calculated by:

$$n = 1 - (\gamma_d \div G_s \gamma_w)$$

γ_d = Dry unit weight of soil
G_s = Specific gravity of the solids
γ_w = Density of water

Seepage Calculations

In the following estimation, the time for leakage from a manure holding pond to reach an underlying aquifer through cracked till uses certain assumptions:

1) the pond is excavated 15 ft into a 100 ft thickness of till and the top of the pond is 5.0 ft below the surface of the ground,
2) water is assumed to fill cracks in the till that extend beyond the pond bottom to a depth of 30 ft (twice the distance seen in test pits), so that the "pond blanket" is a 70 ft thickness of uncracked glacial till above an aquifer,
3) soil dry unit weight 110 pounds per cubic foot = 1.76 g/cc
4) soil hydraulic conductivity is 1 × 10E-7 cm/sec.
5) specific gravity of the soil solids is estimated as 2.70 g/cc. (A range of 2.60 to 2.80 is common.)

$$v = k\left(\frac{H+d}{d}\right) = 1 \times 10^{-7}\left(\frac{25+70}{70}\right) = 1.36 \times 10^{-7}\ \text{cm/sec}$$

$$n = 1 - (\gamma_d \div G_s\gamma_w) = 1 - \left(\frac{1.76}{2.70 \times 1}\right) = 0.35$$

Seepage Velocity = $v \div n = 1.36 \times 10^{-7}$ cm/sec ÷ 0.35 = 3.9 × 10^{-7} cm/sec = 0.40 ft/yr.

Time for water to move through till below the pond into an aquifer: 70 ft thickness of till ÷ 0.40 ft/yr = 175 years.

Although these calculations are based on estimated properties, it is apparent that even if cracks in till extend to a depth of 30 ft (which is beyond that depth seen by the author), it takes a long time for water to move downward through glacial till below the cracks.

CONCLUSIONS

The data printed in Table 1 should be considered only a first step towards evaluating the possible contamination of aquifers and the recharge time for aquifers. The table should be added to as additional test results are acquired. More useful than the test results from these small samples would be the logs of many drill holes correlated with laboratory tests and in-place field studies of soil hydraulic conductivity. In his paper in the aforementioned issue of *The Ohio Journal of Science*, Haefner (2000) describes the difficulties and methods of performing field testing. Field hydraulic conductivity tests could be made at depth intervals of 1.5 m or 3.0 m (5.0 or 10 ft), between depths of 6.0 m (20 ft) and the top of an aquifer. With the collection of data from an adequate number of tests and the evaluation of the hydraulic conductivity of Ohio's glacial till, the possibilities of aquifer contamination from sources of pollution will be known.

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